Comparison of Ultra-Stable BVA Oscillators

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BIOGRAPHY

Alexander Kuna was born in 1978. He graduated from the Faculty of Electrical Engineering (FEE), Czech Technical University, Prague, in 2004. He is a PhD student at FEE. With the IPE he is since 2005 where he is working on precision frequency-stability measurement.

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Dr. Ludvík Šojdr was born in 1934. He graduated from the Military Technical Academy, Brno, in 1957. In 1980 he obtained the CSc degree from the Czech Technical University, Prague. He had been working in industrial research on quartz oscillators and stability measurement until 1996. Since then he is with the IPE.

Dr. Patrice Salzenstein was born in 1970. He holds a Master and engineering diploma (EUDIL, Lille 1993) and a PhD Doctorate in Electronics (University of Lille, 1996). Between 1996 and 2001 he worked in Thales and Alcatel private research laboratories and then joined CNRS where he manages a calibration laboratory and is involved in research in time and frequency.

Dr. Frédéric Lefebvre was born in 1964. He graduated from E.F.R.E.I, in France, in 1985. Since then he has been working in time and frequency metrology in C.E.P.E, and Thales Airsys for high-frequency ultra-stable sources. 10 years ago he joined OSCILLOQUARTZ R&D department, working and doing research on very high stability oscillators.

INTRODUCTION

This paper is a continuation of an earlier discussion on frequency stability measurement of ultra-stable BVA quartz oscillators we have presented in [1]. Here we will describe the results obtained in two measurement campaigns performed in June and October 2007 with five BVA oscillators.

The measured oscillators were 5 MHz Oscilloquartz 8600/8607 units [2], [3], [4] with extremely small flicker frequency modulation (FFM) floor on the order of 10^{-14} in terms of Allan deviation, $\sigma_y(\tau)$. The two best units have showed FFM as small as $\sim 4\text{x}10^{-14}$ which is to our knowledge the lowest FFM ever reported for a quartz oscillator.

These exacting measurements require a highly sensitive phase (time) comparison system and also a stable and non-interfering environment which, if not ensured, may distort the estimation of the inherent stability of the oscillators. The two campaigns allowed us to carry out a number of repeated measurements of all combinations of the oscillator pairs in different periods of day and week, and some of the measurements were repeated five months later. The comparisons of most interest were those with the two OSA's best reference oscillators performed in the October campaign.

BASIC CONSIDERATIONS

Following the measurement model we have discussed in [1], the comparison of a pair of oscillators *m* and *n* results in pair time variations $x(t)_{m,n}$ with corresponding Allan deviation $\sigma_y(\tau)_{m,n}$ as a measure of frequency stability. In a perfect measurement of two uncorrelated oscillators, i.e. with a near-ideal comparison system and in stable and non-interfering measurement conditions, the resulting stability $\sigma_y(\tau)_{m,n}$ would be equal to the inherent (true) pair stability ${}^{P}\sigma_y(\tau)_{m,n}$ composed of two inherent individual stabilities

$$ {}^{P}\sigma_y(\tau)_{m,n}{}^2 = \sigma_y(\tau)_m{}^2 + \sigma_y(\tau)_n{}^2 \qquad (1) $$

If we have $N \geq 3$ uncorrelated oscillators of comparable performance and if the random processes involved can be presumed stationary with respect to $\sigma_y(\tau)$ than we can determine the individual stabilities $\sigma_y(\tau)_1$, …, $\sigma_y(\tau)_N$ by making use of the N-cornered hat method.

In a real measurement the model of resulting stability $\sigma_y(\tau)_{m,n}$ takes a more complex form

$$ \sigma_y(\tau)_{m,n}{}^2 = {}^{P}\sigma_y(\tau)_{m,n}{}^2 + {}^{C}\sigma_y(\tau)^2 + {}^{M}\sigma_y(\tau)^2 \qquad (2) $$

where ${}^{C}\sigma_y(\tau)$ is the disturbing inherent instability of the comparator and ${}^{M}\sigma_y(\tau)$ is the additional spurious instability due to measurement conditions (we assume that all components are uncorrelated). Obviously, the inherent comparator instability ${}^{C}\sigma_y(\tau)$ could only be found by testing the comparator with perfect signals (${}^{P}\sigma_y(\tau)^2 << {}^{C}\sigma_y(\tau)^2$) in perfect measurement conditions (${}^{M}\sigma_y(\tau)^2 << {}^{C}\sigma_y(\tau)^2$). We may presume that the inherent variations ${}^{C}x(t)$ resulting in ${}^{C}\sigma_y(\tau)$ are random processes that are stationary with respect ${}^{C}\sigma_y(\tau)$ and as such ${}^{C}\sigma_y(\tau)$ is well reproducible within statistical uncertainty. This is not so, however, with the disturbing processes that make up ${}^{M}\sigma_y(\tau)$. These may occur irregularly thus making the short-term $\sigma_y(\tau)_{m,n}$ dependent on the time of measurement. Therefore when we compare the same oscillator pair repeatedly, we have for the *i*-th comparison

$$\sigma_y(\tau)_{m,n,i}{}^2 = {}^{P}\sigma_y(\tau)_{m,n}{}^2 + {}^{C}\sigma_y(\tau)^2 + {}^{M}\sigma_y(\tau)_i{}^2 \qquad (3)$$

We presume that the comparator used in our measurements satisfies the condition ${}^{C}\sigma_y(\tau)^2 << {}^{P}\sigma_y(\tau)_{m,n}{}^2$ for the whole range of τ of interest so that we can write

$$\sigma_y(\tau)_{m,n,i}{}^2 \sim {}^{P}\sigma_y(\tau)_{m,n}{}^2 + {}^{M}\sigma_y(\tau)_i{}^2 \qquad (4)$$

and we can consider that at τ_r the best estimate of ${}^{P}\sigma_y(\tau_r)_{m,n}$ is the minimum of $\sigma_y(\tau_r)_{m,n,i}$ over all repeated measurements.

A question arises about the impact of the measurement bandwidth on the resulting $\sigma_y(\tau)_{m,n,i}$. Solving the frequency-to-time domain conversion integral [5]

$$\sigma_y(\tau)^2 = [4/(\pi\tau\nu_0)^2]\int_0^\infty L(f)(\sin \pi\tau f)^4\, df \qquad (5)$$

for the power-law model of $L(f)$ shows that the Allan variance depends on the bandwidth only for the white phase and flicker phase modulations (WPM, FPM). Thus the oscillator FFM floor, which was of prime interest in our measurement, is independent of the measurement bandwidth. However, if the bandwidth is excessive, a large phase noise can mask the FFM floor in the $\sigma_y(\tau)$ plot as it is illustrated on a model in Fig.1. by making use of the power-law noises (WPM, FFM and random-walk frequency) generated by Stable32 [6], [7], [8]. The amount of generated FFM is $\sigma_y(\tau) = 4\text{x}10^{-14}$. The bandwidth of the upper plot is hundred times larger than that of the lower plot.

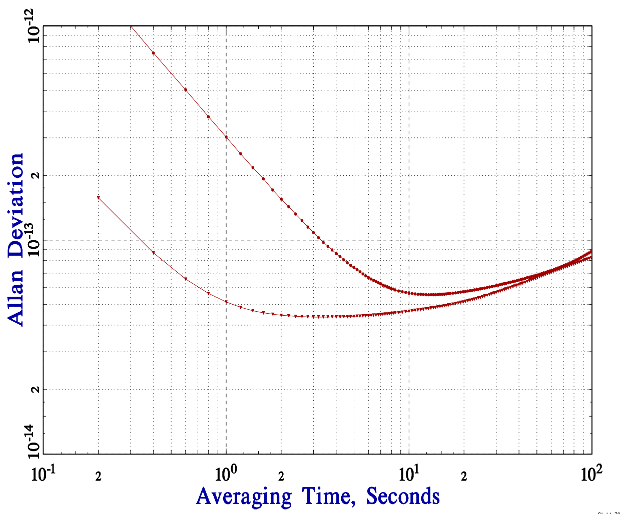

Fig.1. A model signal measured with a different bandwidth.

INSTRUMENTATION

The principal device used in our comparisons was the IPE2 laboratory phase (time) comparator [9], [10], based on the classical dual-mixer time-difference multiplication (DMTDM) [11], [12], [13], [14], [15], [16]. The comparator makes use of a SR620 time-interval counter. The common signal of IPE2 is provided from a 5 MHz Milliren MTI260-504A quartz oscillator which is offset by 5 Hz and further low-noise amplified to the power level of +11 dBm with WPM of $L(f) = -161$ dBc/Hz. Given the 5 Hz beat-note, the IPE2 provides the basic sampling interval of 0.2 ms. The measurement equivalent noise bandwidth is ~24 Hz. This value has been verified by measuring a large-WPM quartz oscillator in the time and frequency domains and then using the $L(f)$ to $\sigma_y(\tau)$ conversion through (5). The IPE2 background instability, represented by ${}^{C}\sigma_y(\tau)$ in (3), was tested several times by two signals power-split from the BVA oscillator s/n 291. The test result calculated from 27,000 samples is shown in Fig.2. The variations have a character of flicker phase modulation (FPM) with $\sigma_y(\tau) \sim 7\text{x}10^{-15}/\tau$ near $\tau = 1$ s.

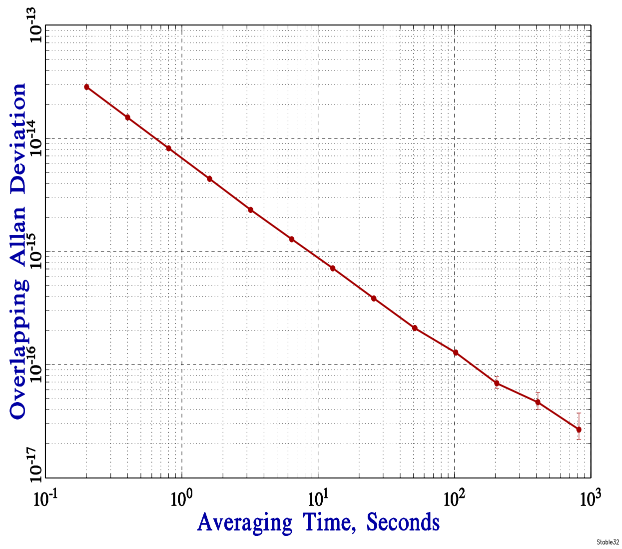

Fig.2. Background instability of the IPE2 comparator.

All the BVA oscillators were put into identical extra cases each with an arrangement for fine tuning with a resolution better than $1\text{x}10^{-12}$. This allowed to maintain the measured oscillators quasi-synchronous which is the basic requirement for reducing the noise of the DMTDM common oscillator [17]. The extra casing also improved the shielding of the oscillators.

MEASUREMENT CONDITIONS

The IPE laboratory for ultra-sensitive stability measurement is housed in a shielded underground vault which ensures relatively stable environment and reduced electromagnetic interference. Since the shielding is far from perfect, interference from other laboratories can be frequently observed at this precision level. This is typically what we model by the term ${}^{M}\sigma_y(\tau)_i$ in (3).

During all measurements the comparator was battery powered. In the June campaign the BVA oscillators were powered from Statron 2229 double AC-DC sources that exhibit a 2 mV rms ripple. These sources had a battery back-up using a DC-AC power convertors. In the October campaign the three best BVA oscillators (s/n 199, 543 and 567) were powered from batteries, the two other were powered from Statron 2229 as in June. The lights in the room were also powered from batteries.

The room temperature was maintained at 25 ± 1ºC. No other instruments except those performing the comparison were active.

PERFORMED COMPARISONS

The five oscillators measured in the two campaigns are shown in Table.1. For simple referencing we denote them by capital letters in accordance with [1] (C is omitted because it denotes the s/n 102 oscillator which was not measured this time.)

Table 1.

Type	Cut	S/N	Possessed by	Jun	Oct	Name
8600	AT	291	IPE	x	x	A
8600	AT	315	IPE	x	x	B
8607	SC	199	FEMTO-ST	x	x	D
8607	SC	543	OSA	x	x	E
8607	SC	567	OSA		x	F

In the June campaign (three weeks) we had four oscillators available (two AT cuts and two SC cuts) and we measured all six oscillator pairs: A-B (14), A-D (15), A-E (13), B-D (13), B-E (14) and D-E (15). The number in parentheses is the number of repeated comparisons. All oscillators had been at least in one-week continuous operation before the measurement started.

In the October campaign (five days) we had five oscillators available but we measured only the three best SC-cut oscillators as follows: D-E (15), D-F (15), E-F (16). The oscillators D, E, F were powered from batteries during their transportation to IPE.

COMPARISON RESULTS

June 2007

In Fig.3 to Fig.8 there are results for all six possible oscillator pairs and for all performed measurements. Each pair stability $\sigma_y(\tau)_{m,n,i}$ has been calculated from ~10,000 samples using the Stable32 code as the basic analysis tool. Before each calculation, outliers and linear frequency drift were removed. The uncertainties are omitted.

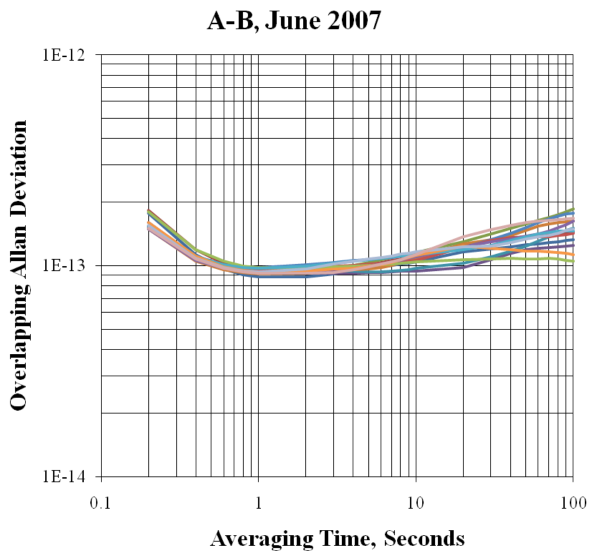

Fig.3. A-B pair stability (14 measurements).

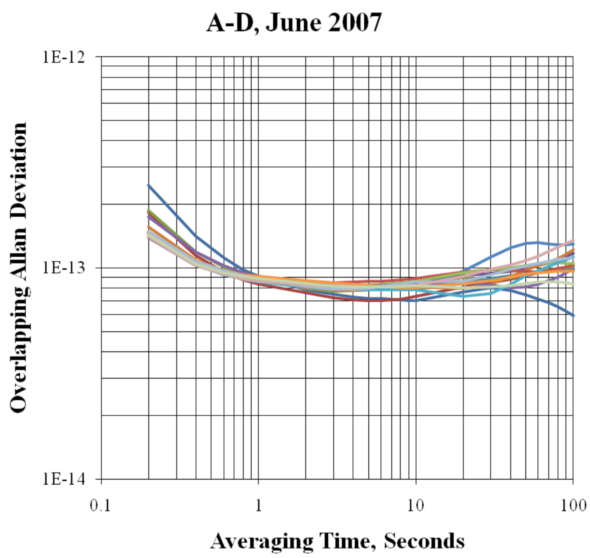

Fig.4. Stability of A-D pair (15 measurements).

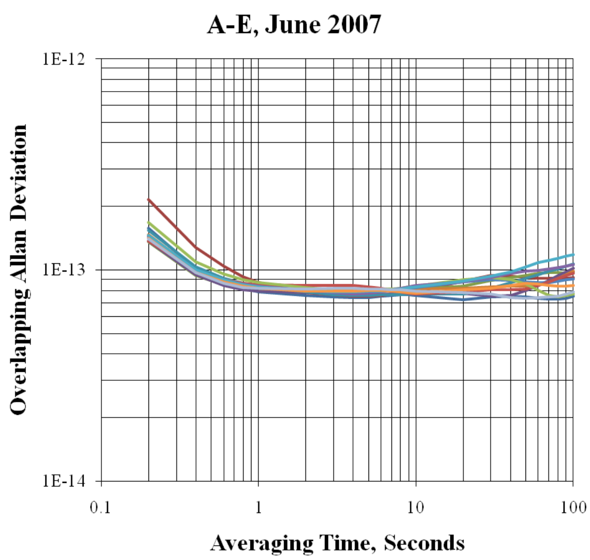

Fig.5. Stability of A-E pair (13 measurements).

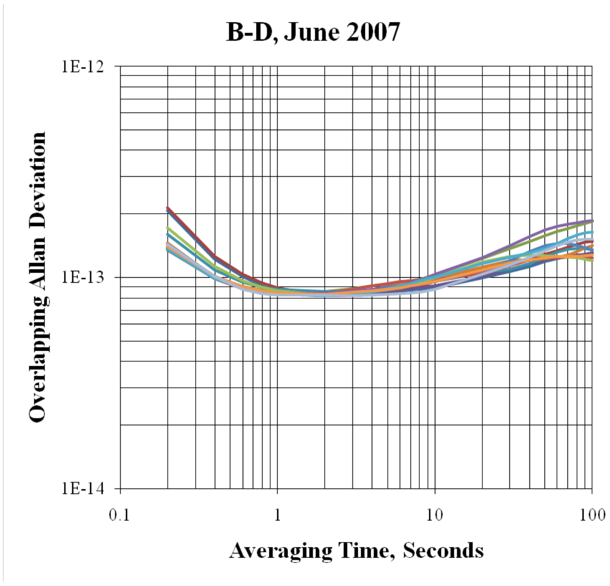

Fig.6. Stability of B-D pair (14 measurements).

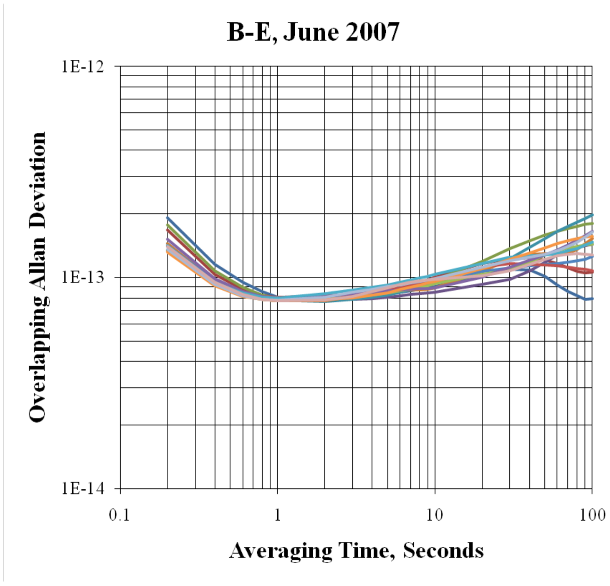

Fig.7. Stability of B-E pair (14 measurements).

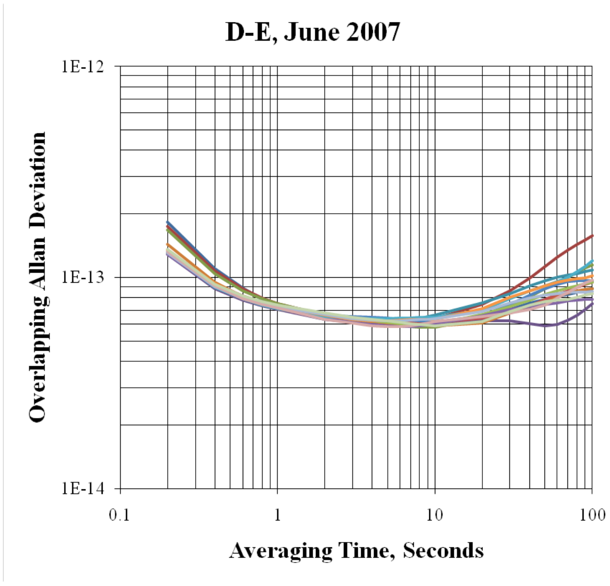

Fig.8. Stability of D-E pair (15 measurements).

In all pairs we can observe a large dispersion of $\sigma_y(\tau)_{m,n,i}$ at smaller averaging intervals where WPM prevails. This can be explained by poorer measurement conditions that increase the component ${}^M\sigma_y(\tau)_i$ in (3) at small τ. The effect manifest itself as if there were several levels of perturbation of the measurement conditions (i.e. several levels of ${}^M\sigma_y(\tau)$). This can be clearly seen in Fig.8 where the dispersion of $\sigma_y(\tau)_{m,n,i}$ at small τ does not seem random. This effect is also observable in other measurements.

Using the four-cornered hat where all $\sigma_y(\tau)_{m,n,i}$, ($m = 1, \ldots, 4$, $n = 1, \ldots, 4$, $m \neq n$) entered the system of equations, we have calculated individual stabilities $\sigma_y(\tau)_A$, $\sigma_y(\tau)_B$, $\sigma_y(\tau)_D$ and $\sigma_y(\tau)_E$ shown in Fig.9. The four-cornered hat results in Fig. 10 are based on the “justifiable minimum” approach we have discussed in [1]. In this case the values $\sigma_y(\tau_r)_{m,n}$ entering the hat are min $[\sigma_y(\tau_r)_{m,n,i} + u(\tau)_{m,n,i}]$ over all i where $u(\tau)_{m,n,i}$ is the statistical uncertainty. A small improvement is observable for the best oscillator.

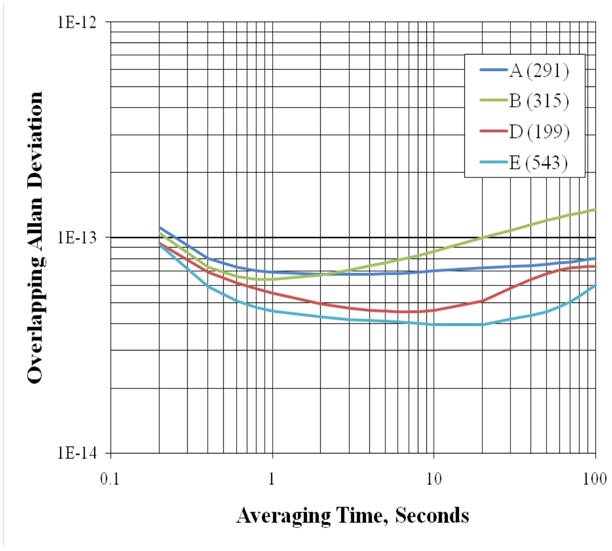

Fig.9. Individual stabilities calculated from all measurements.

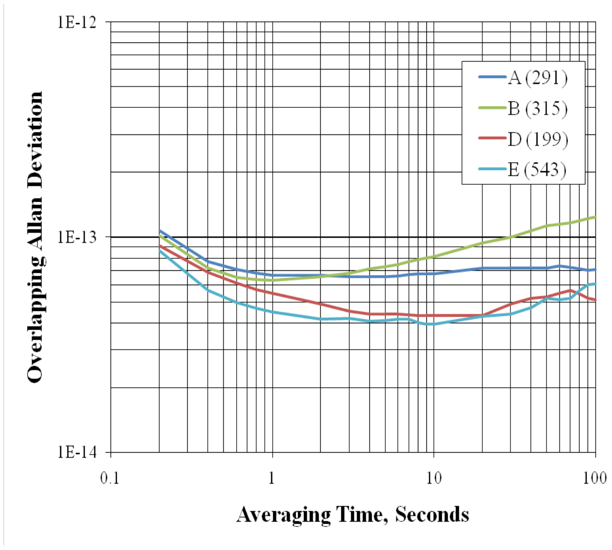

Fig.10. Individual stabilities calculated from “justifiable

minimums".

October 2007

As mentioned previously, in this October measurement we concentrated mainly on the three best SC-cut oscillators D, E and F. The results for the three pairs are shown in Fig.11 to 13. Each pair stability $\sigma_y(\tau)_{m,n,i}$ has been calculated from ~10,000 samples. Outliers and linear frequency drift were removed before each calculation.

The effect of changes in measurement conditions is not observable as in June. We can observe only two "outlier" measurements: one in Fig.11 and one in Fig.12. The results of the best oscillator pair shown in Fig.13 can be considered excellent.

The three-cornered hat decomposition into individual stabilities $\sigma_y(\tau)_D$, $\sigma_y(\tau)_E$, $\sigma_y(\tau)_F$ using all $\sigma_y(\tau)_{m,n,i}$ is depicted in Fig.14. The minimum FFM floor shows the oscillator E ($\sigma_y(\tau)_E = 4.3\text{x}10^{-14}$). The "justifiable minimum" method has brought no observable improvement.

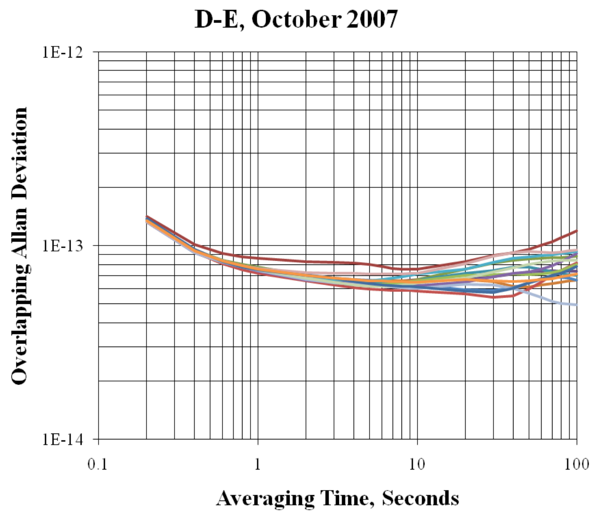

Fig.11. Stability of D-E pair (15 measurements).

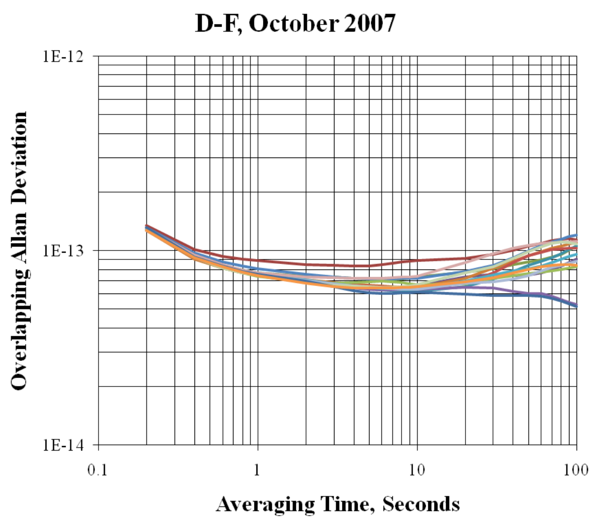

Fig.12. Stability of D-F pair (15 measurements).

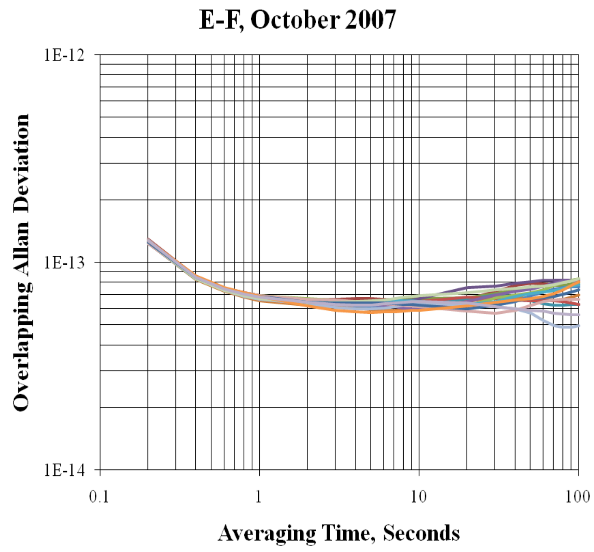

Fig.13. Stability of E-F pair (16 measurements).

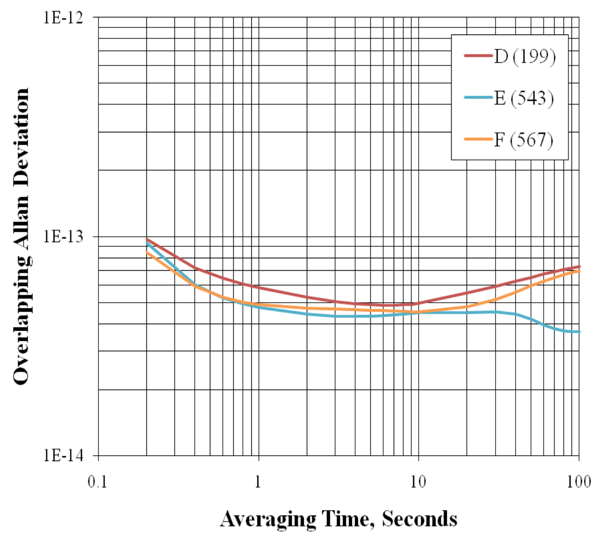

Fig.14. Individual stabilities calculated from all measurements.

It should be noted that we were not able to determine the uncertainties of the decomposed stabilities.

October versus June measurements

The two campaigns have allowed us to compare the $\sigma_y(\tau)_{D,E}$ pair stability obtained over a five-month span. Comparing the averages of the June and October measurements we obtain the results shown in Fig.15 along with 95% statistical uncertainties.

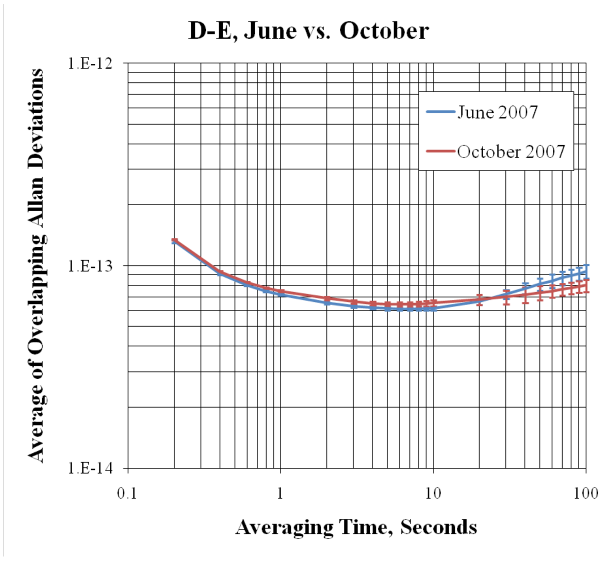

Fig.15. June vs. October measurement.

CONCLUSIONS

This extensive measurement of high-performance BVA oscillators has confirmed what we have already hinted in [1] that one measurement even with robust enough statistics is not sufficient to obtain a good estimate of the inherent short-term stability of the best oscillators. This is due to changes in measurement conditions and not in oscillator performance. Thus in order to have knowledge of the oscillator performance, repeated measurements are needed. These of course are costly but there seems no other way if the measurement conditions are not perfect enough which is also the case of the IPE laboratory.

The inherent FFM floor of ~$4x10^{-14}$ found for the OSA reference oscillators E and F is, in our view, an excellent result. Thus at averaging intervals of seconds, these oscillators provide better stability than the best active hydrogen masers (e.g. Symmetricom specifies for their MHM 2010 maser $\sigma_y(\tau) \sim 2x10^{-13}$ at 1 s in 1 Hz bandwidth).

The measurement has also confirmed a very good performance of the IPE2 DMTDM comparator. Currently at IPE we are working on a new version designated IPE3 with a target background FPM of $5x10^{-15}$ at 1 s in 24 Hz bandwidth.

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